Irish Journal of Agricultural and Food Research **48:** 21–34, 2009

Conservation characteristics of baled grass silages differing in duration of wilting, bale density and number of layers of plastic stretch-film

G. Keles[1*], P. O'Kiely[1]†, J.J. Lenehan[1] and P.D. Forristal[2]
[1]*Teagasc, Grange Beef Research Centre, Dunsany, Co. Meath, Ireland*
[2]*Teagasc, Crops Research Centre, Oak Park, Co. Carlow, Ireland*

The effects of duration of wilting, bale density and number of layers of plastic stretch-film used to wrap bales on the conservation characteristics of baled grass silage was investigated. Grass from the primary growth of a *Lolium perenne* dominant sward was wilted for 24, 48 or 72 h. For each duration of wilting, 54 cylindrical bales (1.2 m nominal diameter) were made with the baler at a high or low density setting for alternate bales. Bales were wrapped with 2, 4 or 6 layers of plastic stretch-film and stored outdoors for 295 days. Two layers of plastic stretch-film resulted in inferior preservation, lower digestibility and extensive mould growth and deteriorated silage. Substantial improvement occurred to each of these characteristics from applying four layers of stretch-film (P<0.05), while six layers of stretch-film brought little further improvement. When four or six layers of stretch-film were used, extensive wilting restricted fermentation and improved the standard of preservation with the apparently difficult-to-preserve herbage used in this experiment. However, under the anaerobic conditions provided by four or six layers of stretch-film neither progressive wilting nor bale density had a major effect on digestibility, or the extent of surface mould growth or deteriorated silage. It can be concluded that a minimum of four layers of conventional black plastic stretch-film were required to achieve suitably anaerobic conditions, and that the additional benefits from six layers were small. Once anaerobic conditions were achieved, extensive wilting improved the conservation characteristics of baled grass silage made from a difficult-to-preserve crop, whereas bale density had little impact.

Keywords: bale density, baled silage; conservation characteristics; stretch-film; wilting

†Corresponding author: padraig.okiely@teagasc.ie
*Current address: Bahri Dagdas International Agricultural Research Institute, Konya, Turkey

Introduction

Silage is made on approximately 86% of Irish farms and baled silage accounts for about one-third of the area of grassland harvested for silage (O'Kiely *et al*., 2002). Fundamental to the efficient ensilage of grass is the rapid achievement of anaerobic conditions together with the inhibition of the activity of undesirable anaerobic microorganisms (McDonald, Henderson and Heron, 1991).

Although the principles governing the preservation of baled silage are the same as for the more conventional precision–chop or flail silages, the chemical and microbiological composition of baled silage frequently differs from that of conventional silages (McEniry *et al*., 2006 and 2008). The differences between baled and conventional silages result from the fact that the systems used to produce them address the fundamental principles of ensilage somewhat differently and/or differences in the grass crops used for ensilage (Forristal and O'Kiely, 2005). Baled silage is characterised by its unique individual-package storage system and has 6 to 8 times the surface area in contact with the plastic stretch-film compared to conventional bunker silage (Forristal and O'Kiely, 2005). About half of the silage volume is within 15 cm of the stretch-film, and consequently deterioration caused by air ingress can affect a substantial proportion of the silage (Forristal and O'Kiely, 2005). The grass in bales is ensiled either un-chopped or comminuted using a fixed-knife system, in contrast to the high speed chopping and laceration systems used in precision-chop or flail harvesting systems. In addition, porosity within bales can range from 0.5 to 0.8 of the bale volume so if air enters past the stretch-film it can penetrate deeply into the bale (Forristal and O'Kiely, 2005). In baled-silage systems, anaerobic conditions are achieved by wrapping the bale in adequate plastic stretch-film. However, the evidence from on-farm studies is that damage to the stretch-film is due to mechanical and wildlife factors, and this can result in extensive fungal growth (O'Brien *et al*., 2007 and 2008). It can be speculated that increasing the amount of stretch-film applied should reduce the extent of fungal activity provided the integrity of the stretch-film seal is maintained throughout ensilage. In addition, increasing the density of bales and thereby reducing bale porosity should reduce the extent of silage deterioration in circumstances where the integrity of the stretch-film seal is compromised.

Wilting is generally an integral part of baled-silage systems. Besides aiding preservation by reducing the water activity in the herbage (Greenhill, 1964), successful wilting also prevents effluent production. In addition, from a practical point of view, it can reduce the number of bales produced per hectare thereby reducing the overall production costs. However, the porosity of bales increases with increasing herbage dry matter (DM) concentration and the more restricted fermentation can present less inhibitory conditions for fungal growth if air penetrates the silage mass through insufficient or damaged stretch-film.

McEniry *et al*. (2007), using laboratory silos, demonstrated that both achieving anaerobic conditions and increasing herbage DM concentration have much larger effects on silage composition than increasing the compaction of silages or shortening the chopping length. However, there is little published information on the interactions of these factors using silage bales. The objective of this experiment was to assess the effects of grass DM concentration, bale density and the number of layers of plastic stretch-film used to wrap bales on silage composition and mould development in baled silage.

Materials and Methods

The experiment was organized in a 3 (duration of wilting) × 2 (bale density) × 3 (number of layers of plastic stretch-film) factorial arrangement of treatments. Herbage was wilted for 24 (W24), 48 (W48) or 72 (W72) h after mowing. After each duration of wilting, 54 bales were made using two different baler density settings. At each of these bale densities, nine bales were wrapped in each of 2, 4 or 6 layers of plastic stretch-film.

Baling procedure

The experiment was conducted at Teagasc, Grange Beef Research Centre, Dunsany, Co. Meath (53°31' N, 06°40' W). A *Lolium perenne* dominant permanent grassland sward was mown to a stubble height of approximately 6 cm on 25 May with a mower conditioner set to place wide windrows on the stubble. The herbage remaining after W24 and W48 were harvested was tedded, and subsequently windrowed immediately before baling. After each wilting time, 54 bales were made from every third windrow in the field using a round baler (Class™ Rollant 46 Roto Cut Baler) with the stationary cutting blades engaged. High and low bale densities were obtained by operating the baler at a high (DH) or low (DL) density setting for alternate bales. At baling, bales were tied with netting and then transported to the storage area where they were core sampled (McEniry *et al*., 2006) and weighed. The core holes were then refilled with chopped grass from the same sward. The core samples from each bale were combined to produce a single composite sample (assayed for DM, crude protein (CP), *in vitro* dry matter digestibility (DMD) and ash) per bale. In sequence, individual bales of the same density were wrapped (McHale™ 991 BE wrapper) with two (P2), four (P4) or six (P6) layers of black plastic stretch-film (Silawrap™, Volac; 25 µm film layers thickness; stretched by 70 percent during wrapping), giving nine bales per treatment combination. Bales were stored on their curved side on an outdoor grass base (all bales stored at ground level) for 295 days. They were then core sampled (McEniry *et al*., 2006) and a single composite sample per bale was analysed for DM, CP, DMD, ash, pH, water-soluble carbohydrate (WSC), and fermentation products (ammonia-N (NH_3-N), lactic acid (LA) and volatile fatty acids (VFA; acetic, propionic and butyric acids)).

Visual assessment of silage bales

Immediately prior to core sampling at the end of the 295-day storage period each bale was scored for visible mould growth and deteriorated area on the bale surface. Visible mould growth was assessed as mould patch area (MPA; expressed as a proportion of the visible surface of the bale) and its depth (MD), and these were recorded separately for both the ends and barrel of each bale. MPA was measured with reference to a plastic grid that was placed over each mould patch, while MD was measured where a 3 to 15 cm deep cut was made across the centre of each mould patch. The deteriorated area on the visible surface of bales (DA) was identified as forage that would be no longer edible by cattle and was measured and expressed in a similar manner to MPA. The total area damaged (TD) was the sum of MPA and DA on the bale surface. The depth of the deteriorated silage (DD) was measured only on the barrel of the bale, using a similar procedure as described for MD. After core sampling, bales were split open and assessed for visible mould interspersed through the bale (i.e. flecking).

Analytical procedures

Grass DM concentration was determined by drying at 98 °C for 16 h in an oven with forced air circulation. Sub-samples dried at 40 °C for 48 h were milled (1 mm screen) and used for determination of CP (N × 6.25) using a LECO FB 428 nitrogen analyser, ash (550 °C for 5 h) (AOAC, 1990) and *in vitro* DMD (Tilley and Terry, 1963), with the modification that the final residue was isolated by filtering rather than centrifuging.

The DM concentration of each silage sample was determined by drying at 40 °C for 48 h. These dried samples were then used to analyse for CP, DMD and ash as described for dried fresh herbage. The pH was determined on an aqueous extract using a pH electrode (Hanna Instruments, HI98127). An aqueous extract was also used for estimating LA (using a Ciba/Corning Diagnostic 550 Express clinical chemistry analyzer according to the method of Boehringer Mannheim (catalogue No. 139084)), NH_3-N (Sigma diagnostics method for plasma ammonia procedure no. 171-uv) and VFA (by gas liquid chromatography; according to Ranfft, 1973). Water-soluble carbohydrates were determined according to Wilson (1978).

Statistical analysis

The experimental data were analysed by three-way analysis of variance for a linear model that accounted for the main effects of duration of wilting, bale density and the number of layers of stretch-film used, and all two-way and three-way interactions using Proc GLM (SAS, 2000). Because of the high incidence of both low and high values, and thus their non-normal distribution, arcsin transformation was used for MPA, DA and TD as a percentage of visible bale surfaces. Comparisons between treatments were made using the least significant difference procedure.

Results

Grass composition

The mean (s.d.) weights of DL and DH bales at ensiling were 560 (55.0) and 708 (39.0) kg, 521 (63.2) and 638 (32.2) kg, and 427 (35.1) and 507 (16.7) kg for the W24, W48 and W72 wilting treatments, respectively. Dry matter densities (kg/m^3) for DL and DH bales at ensiling were estimated (assuming a standard bale volume of 1.36 m^3 – i.e., cylindrical bale of 1.2 m diameter and 1.2 m width) as 118 and 149, 123 and 151, and 137 and 162 for the W24, W48 and W72 wilting treatments, respectively. The meteorological conditions during wilting and baling are summarised in Table 1.

The mean chemical composition of the herbages at ensiling is summarized in Table 2. Extending the duration of wilting increased the DM concentration of the herbage ($P<0.001$), but had no impact ($P>0.05$) on CP concentration. Wilting for 72 h resulted in a lower DMD ($P<0.001$) and a higher ash concentration ($P<0.001$) than wilting for 24 or 48 h.

Mouldy and deteriorated areas

No flecking of mould was found through the bales. Mould patch area on both the bale ends and the total surface area increased ($P<0.001$) with each increment in the duration of wilting, while MPA on the barrel and MD on both the bale ends and the barrel were larger ($P<0.05$) for W48 and W72 than for W24 (Table 3). Bale density had no effect ($P>0.05$) on MPA or MD while the effect of the number of layers of stretch-film was significant ($P<0.001$) for all MPA and MD measurements. Bales wrapped

Table 1. Weather conditions during wilting

Date	Rainfall (mm)	Relative humidity (%)	Sunshine (h)	Solar radiation (Wh/m^2)	Temperature (°C)	
					Min.	Max.
May-24	0	59.2	13.0	29.38	4.8	14.6
25	0	56.8	13.5	27.28	1.9	17.8
26	0	81.9	3.0	16.36	5.2	19.2
27	0	77.1	9.0	19.58	7.7	16.9
28	0	74.3	12.6	27.76	8.4	18.4

Table 2. Chemical composition of herbage immediately after baling (but before wrapping in plastic stretch-film)

Component[1]	Duration of wilting (h)			s.e.	Significance
	24	48	72		
DM (g/kg)	286	321	434	6.9	***
CP (g/kg DM)	171	172	171	1.9	
DMD (g/kg)	743	751	726	3.0	***
Ash (g/kg DM)	100	103	110	1.4	***

[1] DM = dry matter; CP = crude protein; DMD = *in vitro* dry matter digestibility.

with P2 had the largest MPA and the deepest MD on the bale ends, while MD on the barrel was smaller for P6 than for P2 or P4.

There were no significant two-way interactions between the duration of wilting and bale density or between bale density and the number of layers of stretch-film, and no three-way interactions, for any MPA or MD measurements. A significant two-way interaction occurred between the duration of wilting and the number of layers of stretch-film for all MPA and MD measurements. Bales made from W48 herbage and in particular from W72 herbage and then wrapped with P2 usually had the largest ($P<0.05$) MPA and the deepest ($P<0.01$) MD on the bale.

The duration of wilting had no effect ($P>0.05$) on the DA or DD measurements. High density was associated with greater ($P<0.05$) DA and deeper ($P<0.001$) DD compared with DL for all DA and DD measurements. Wrapping bales with P2 resulted in greater ($P<0.001$) DA and DD values than wrapping with P4 or P6.

There was a significant two-way interaction between the duration of wilting and bale density for all DA and DD measurements, with DL bales made from W48 herbage generally having smaller DA and DD values ($P<0.05$). Interactions also occurred between the duration of wilting and the number of layers of stretch-film. In general, bales made from W24 or W72 herbage and then wrapped with P2 had larger ($P<0.01$) DA and DD values than the bales made from W48 herbage and then wrapped with P2. Both DA and DD values were generally largest for DH bales wrapped with P2, followed by DL bales wrapped with P2. The occurrence of deterioration was virtually eliminated by increasing to P4 with DL bales but it was necessary to go to P6 with DH bales to get the same effect. Three-way interactions occurred for DA values on the barrel and total area of the bale, and for DD values on the barrel. The extent of deterioration

Table 3. Mean values, for all combinations of duration of wilting, bale density and number of layers of stretch-film, for mould patch area (MPA) as percentage of area of bale ends, barrel and total, mould depth (MD) on bale ends and barrel, deteriorated area (DA) as percentage of area of bale ends, barrel and total, deteriorated depth (DD) on the bale barrel, and total damaged area (TD) as percentage of bale surface

Factors			MPA[1]			MD (cm)		DA[1]			DD (cm)	TD[1]
Wilting (h)	Density	Layers	End	Barrel	Total	End	Barrel	End	Barrel	Total	Barrel	
24	low	2	2.5 (<1)	2.3 (<1)	2.7 (<1)	1.1	1.5	76 (94)	84 (99)	78 (96)	54	81 (98)
24	low	4	3.1 (<1)	11.4 (4)	9.9 (3)	2.2	8.4	0 (<1)	0 (<1)	0 (<1)	0	10 (3)
24	low	6	0.5 (<1)	3.3 (<1)	2.8 (<1)	1.1	2.2	0 (<1)	0 (<1)	0 (<1)	0	3 (<1)
24	high	2	14.7 (6)	6.7 (1)	11.1 (4)	5.8	3.0	73 (91)	77 (95)	75 (93)	54	79 (96)
24	high	4	1.1 (<1)	8.0 (2)	5.9 (1)	1.3	5.0	3 (<1)	0 (<1)	2 (<1)	2	7 (1)
24	high	6	2.2 (<1)	8.1 (2)	6.7 (1)	0.8	4.8	0 (<1)	0 (<1)	0 (<1)	0	7 (1)
48	low	2	17.8 (9)	13.9 (6)	16.7 (8)	6.9	6.6	30 (25)	24 (17)	26 (19)	19	38 (38)
48	low	4	8.3 (2)	14.1 (6)	12.9 (5)	4.7	7.4	0 (<1)	1 (<1)	1 (5.74)	1	13 (5)
48	low	6	3.8 (<1)	7.3 (2)	6.6 (1)	2.2	2.4	0 (<1)	0 (<1)	0 (<1)	0	7 (1)
48	high	2	18.0 (10)	25.7 (19)	23.1 (15)	8.3	8.9	65 (82)	79 (97)	72 (90)	60	77 (95)
48	high	4	6.0 (1)	11.0 (4)	10.1 (3)	3.9	6.4	17 (9)	23 (15)	20 (12)	14	26 (19)
48	high	6	0.6 (<1)	6.2 (1)	4.6 (<1)	0.7	2.0	0 (<1)	0 (<1)	0 (<1)	1	5 (<1)
72	low	2	26.1 (19)	33.2 (30)	30.5 (26)	10.0	10.0	61 (76)	59 (73)	50 (59)	45	68 (86)
72	low	4	5.4 (<1)	3.9 (<1)	5.0 (<1)	2.2	2.4	0 (<1)	0 (<1)	0 (<1)	0	5 (<1)
72	low	6	9.8 (3)	6.4 (1)	8.6 (2)	3.2	3.4	2 (<1)	0 (<1)	1 (<1)	2	9 (2)
72	high	2	23.7 (16)	32.5 (29)	30.2 (25)	9.4	8.9	72 (90)	79 (96)	73 (91)	54	83 (99)
72	high	4	11.0 (4)	8.2 (2)	10.7 (3)	3.1	3.4	3 (<1)	10 (3)	6 (1)	1	16 (8)
72	high	6	8.2 (2)	8.2 (2)	8.6 (2)	2.4	4.6	0 (<1)	0 (<1)	0 (<1)	0	9 (2)
s.e.			2.74	3.49	2.54	1.09	1.07	6.21	5.97	5.72	3.92	5.14
Significance level												
Wilting			***	***	***	***	*					
Density								*	***	***	***	***
Layer			***	***	***	***	***	***	***	***	***	***
Wilting × density								*	***	**	***	*
Wilting × layer			*	***	***	**	***	**	***	***	**	***
Density × layer									**	**	***	*
Wilting × density × layer									*	*	*	*

[1] Mean values are presented on the arcsin-transformed scale with back-transformed values in parentheses.

was more severe (P<0.05) for HD bales made from W48 and W72 herbage and wrapped in P4 rather than in P6.

The duration of wilting had no effect (P>0.05) on TD measurements. High density bales were associated with more (P<0.001) total damage than DL bales. Total damage on the surface of bales decreased (P<0.001) with each increase in the number of the layers of stretch-film.

Two-way interactions between the duration of wilting and bale density occurred for TD measurements. Increasing bale density resulted in more (P<0.05) total damage on W48 bales, and this was repeated to a lesser extent with W72 bales. Bales made from W24 and W72 herbage and wrapped with P2 had the greatest (P<0.001) total damage. It was necessary to go to P6 to get less total damage for W48 bales whereas P4 was adequate with W24 and W72 bales. The largest (P<0.05) reduction in TD value was achieved by P4 or P6 for DL bales whereas P6 was needed with DH bales. A significant (P<0.05) three-way interaction was evident whereby for W48 (but not W24 or W72) silage the extent of total damage was similarly reduced by P4 and P6 with DL bales whereas with DH bales P6 gave a greater (P<0.05) reduction than P4.

Silage composition

Silage chemical composition results are presented in Table 4. Silage DM and WSC concentrations and proportion of LA to other fermentation products (LA/FP) increased (P<0.001), while acetic (AA) and propionic acid (PA) concentrations decreased (P<0.001), with each increment in the duration of wilting. Silages made from W72 herbage had lower (P<0.05) concentration of LA, butyric acid (BA), CP and NH_3-N than the silages made from W24 or W48 herbages. Silage pH was not altered (P>0.05) by the duration of wilting. Silages made from W48 and W72 herbage had a higher (P<0.01) DMD value than silage made from W24 herbage. Bale density had a significant (P<0.05) effect only for WSC concentration, with the value being lower for DH bales. The number of layers of stretch-film had a significant effect on several variables. P2 treatments resulted in reduced (P<0.01) DM, DMD, LA, AA and BA, but increased (P<0.05) CP, ash, pH and NH_3-N values compared to P4 and P6. P2 treatments also reduced (P<0.01) WSC values compared to P6.

There were significant two-way interactions between the duration of wilting and bale density for DMD and WSC values. Bale density influenced DMD only with silages made with W48 herbage, where DH bales had a lower (P<0.05) DMD. Bale density influenced WSC only with silage made from W72 herbage, where DH bales had a lower (P<0.01) residual WSC after fermentation. There were significant two-way interactions between the duration of wilting and the number of layers of stretch-film for DM, CP, DMD, LA and AA values. Increasing from P2 to P4 or P6 resulted in a higher (P<0.01) DM value for W24 or W72 bales, but no increase occurred (P>0.05) for W48 bales. The main increases in DMD due to wilting beyond W24 occurred (P<0.01) only for P2 bales. Similarly the main increase in DMD from P2 to P4 or P6 bales occurred only for W24 silage. The overall lower LA for W72 compared to W24 or W48 occurred (P<0.001) for P4 and P6 but not for P2, while the overall increase in LA from P2 to P4 or P6 occurred for W24 and W48 silages but not for W72 silage. The decline in AA with each increment of wilting occurred (P<0.01) for P4 and P6 but not for P2, while the higher AA for P4 and P6 compared to P2 occurred for W24 and W48 silages but not for W72 silage. Two-

Table 4. Mean values, for all combinations of duration of wilting, bale density and number of layers of stretch-film, for the composition of baled silage

Factors			Silage composition[1]											
Wilting (h)	Density	Layers	DM	CP	DMD	Ash[2]	WSC	pH	LA	AA	PA	BA	LA/FP	NH_3-N
24	low	2	169	187	626	134	13	6.8	39	16.2	1.4	2.3	0.65	276
24	low	4	225	178	697	112	20	4.4	69	33.8	2.2	11.2	0.60	130
24	low	6	228	176	706	112	22	4.3	78	29.7	2.1	9.9	0.66	135
24	high	2	179	192	608	136	11	6.2	35	22.0	2.4	7.1	0.55	185
24	high	4	221	176	706	114	20	4.4	75	33.0	2.5	10.3	0.62	128
24	high	6	244	165	740	108	26	4.3	78	29.8	1.5	7.9	0.67	120
48	low	2	287	166	725	121	34	5.4	52	17.9	0.5	5.2	0.68	143
48	low	4	249	171	717	115	27	4.5	65	21.9	1.3	13.9	0.64	141
48	low	6	265	180	721	117	28	4.3	75	27.3	0.9	5.4	0.70	139
48	high	2	234	181	643	139	25	7.2	34	16.0	0.7	4.4	0.65	200
48	high	4	259	179	706	119	27	4.6	68	21.8	0.9	7.9	0.69	145
48	high	6	278	175	709	118	33	4.4	65	20.5	1.0	11.3	0.67	134
72	low	2	368	172	683	122	46	5.8	37	3.4	0.1	0.9	0.89	136
72	low	4	396	165	705	112	50	4.7	46	3.9	0.0	1.4	0.90	96
72	low	6	377	164	729	115	53	4.6	48	3.9	0.0	1.1	0.91	99
72	high	2	368	168	712	116	38	5.7	41	3.2	0.0	0.7	0.91	134
72	high	4	390	163	735	108	42	4.5	44	3.7	0.1	1.2	0.90	109
72	high	6	407	168	718	113	40	4.5	44	3.7	0.1	1.0	0.90	89
s.e.			11.2	4.97	16.6	6.63	3.00	0.36	4.31	2.42	0.29	1.98	0.03	23.5
Significance level for														
Wilting			***	***	**		***		***	***	***	***	***	***
Density							*							
Layer			***	*	***	***	**	***	***	***		**		***
Wilting × density					*		**							
Wilting × layer			**	*	**				***	**				
Density × layer			*											
Wilting × density × layer														

[1] DM = dry matter (g/kg); CP = crude protein (g/kg DM); DMD = *in vitro* dry matter digestibility (g/kg); WSC = water-soluble carbohydrates (g/kg DM); LA = lactic acid (g/kg DM); AA = acetic acid (g/kg DM); PA = propionic acid (g/kg DM); BA = butyric acid (g/kg DM); NH_3-N = ammonia-N (g/kg N); LA/FP = proportion of LA in total measured fermentation products (i.e., LA+AA+PA+BA).
[2] g/kg DM

way interactions between bale density and the number of layers of stretch-film were significant only for silage DM concentration. Silage DM concentration increased ($P<0.05$) from P2 to P4 to P6 for DH but not for DL bales. There were no significant three-way interactions for silage composition.

Discussion

Grass composition

Field wilting of herbage is often difficult under Irish weather conditions. However, in the present experiment herbage DM concentration had reached 286, 321 and 434 g/kg after 24, 48 and 72 h wilting, reflecting the absence of rain and relatively high solar radiation and low relative humidity. Assuming a DM value of 200 g/kg for the crop at mowing the estimated mean hourly drying rates during sequential 24 h wilting periods were 3.6, 1.5 and 4.7 g/kg, respectively. Similar drying rates under Irish conditions in the absence of rain have been reported by McNamara *et al.* (2002, 2004).

A decline in herbage digestibility during wilting was apparent only between the 48 h and 72 h wilted herbages. The corresponding increase in ash concentration may partly explain this effect, and likely reflects some soil contamination during tedding and windrowing. Losses of soluble carbohydrates due to respiration may also have contributed to the decline in digestibility (Greenhill, 1959).

The DM density of the herbage in the low density bales was similar to the minimum values reported by Huhnke, Muck and Payton (1997) for ryegrass and legume-grass silages of comparable DM concentration. Changing the baler density setting to increase bale density resulted in mean proportional increases in the weight of fresh matter and DM per 1 m^3 of 0.23 and 0.22, respectively. However, the DM densities achieved were not as high as those reported by Jacobsson, Lingvall and Jacobsson (2002). Wilting also influenced bale density at baling, increasing the DM density but decreasing fresh matter density. Thus, the mean proportional increases in DM per 1 m^3 between W24 and W48 and between W48 and W72 were 0.03 and 0.09, respectively, with corresponding proportional decreases in fresh matter density of 0.09 and 0.19. These trends are in accord with Lingvall (2002).

Mouldy and deteriorated area

Overall, extended wilting did not have a consistent effect on total damage to the outer surface of the bale, and this agrees with McNamara *et al*. (2004). In contrast, the extent of visibly-mouldy surface area increased with more extensive wilting, but only under conditions where insufficient stretch-film was applied to the bales (i.e., P2). Thus, where bales were wrapped in enough plastic stretch-film to create adequately anaerobic conditions then extensive mould growth was restricted irrespective of the extent of wilting that had occurred. Conversely, two layers of stretch-film created sufficiently aerobic conditions to permit mould growth, the extent of which increased as herbage DM concentration increased. A proposed explanation for this outcome follows. The oxygen trapped within a bale immediately after wrapping should be utilized by the herbage and its epiphytic microflora within a few hours, and the considerable production of carbon dioxide as a by-product of this residual respiration and then as a by-product of fermentation means that net gas movement during the first 1 to 3 weeks of ensilage will be outwards past the layers of stretch-film. Thus, even where only two layers of stretch-film were used, conditions within the bale should have been relatively anaerobic during the first week or more of ensilage. As shown for the bales wrapped in four or six layers of stretch-film, where relatively anaerobic conditions therefore prevailed, progressively more extensive wilting resulted in more restricted silage fermentation, and the lower concentrations of fermentation products associated with the silages of higher DM concentration presented conditions less inhibitory for mould growth (Woolford, 1975). Consequently, once net gas outflow ceased and air ingress past the two layers of stretch-film commenced, more mould activity could be expected on the higher DM bales. This mould activity, in turn, would have resulted in the metabolism of fermentation products such as lactic acid, and the production of water as a by-product of respiration. The chemical composition of the silages in Table 4 support this explanation. The findings discussed above agree with O'Brien *et al.* (2008) who undertook a survey of baled silage on Irish farms and found (a) a relatively high incidence of visible damage to the stretch-film surrounding bales (thereby permitting localized air ingress), and (b) a greater extent of visible surface mould on bales made from herbage that underwent a longer duration of wilting.

The depth to which visible mould penetrated beneath the surface of the silage bales was closely and positively associated with the extent of mould growth across the bale surface and therefore likely reflects the factors described above.

Wilting for longer than 24 h reduced both the deteriorated area and total damage on the surface of low density bales wrapped in two layers of stretch-film. This effect occurred without any associated change in the extent of visibly mouldy silage. These silages with reduced damage were also the only ones where the change in herbage DM concentration during ensilage was not affected by the number of layers of stretch-film used, and implies that the seal between the layers of film did not break as extensively as with the other treatments thereby resulting in a less extensive ingress of oxygen and possibly of rainwater. The explanation for this finding is not apparent.

Across all factors, two layers of stretch-film proved inadequate for preventing aerobic losses, and this was evident in terms of bale surface damage and the depth of damage beneath the surface. Visually deteriorated silage accounted for a much larger proportion of the bale surface than did mouldy silage and this imbalance was particularly apparent with the wetter silages. Increasing the number of layers of stretch-film from two to four produced a major reduction in aerobic damage, while a further increase to six layers of stretch-film produced a relatively small additional improvement. These results agree with other results obtained under Irish conditions (Forristal *et al.*, 1999), but appear to disagree with some of the results obtained under Scandinavian conditions (Jacobsson *et al*., 2002; Lingvall, Pettersson and Wilhelmsson, 1993 and Heikkila *et al*., 2002) where six layers of stretch-film are routinely recommended. The apparent difference between Irish and Scandinavian results may reflect a requirement for more stretch-film to counteract the higher gas permeability that would be associated with the higher temperature of the stretch-film likely to occur in Scandinavia due to their longer, sunnier days during the summer.

Chemical composition

Dry matter concentration: The relative differences in DM concentration between the three wilting treatments pre-ensiling was maintained post-ensiling. However, silage DM concentrations were proportionally 0.26, 0.18 and 0.12 lower than for the pre-ensiled herbage for W24, W48 and W72, respectively. It is likely that a number of factors contributed to such large changes in DM concentration. Firstly, there could have been some ingress of rainwater between the layers of stretch-film during the 295 days of storage outdoors. This is suggested by the observation that the largest declines in DM concentration were most frequently observed when only two layers of stretch-film were used. Furthermore, an implication of the observation by Hancock and Collins (2006), that bale shape can deform during storage, is that some loosening of the stretch-film could then occur. Such deformation would be more likely with the W24 herbage and with only two layers of stretch-film, and it was with these treatments that the biggest decline in DM concentration occurred. Secondly, the production of water as a by-product of respiration and the loss of DM due to both respiration and fermentation will combine to further reduce silage DM concentration. Thirdly, whereas sampling error due to the uneven distribution of rainwater or of water produced by respiration throughout the bale is unlikely to have been a significant factor (due to the core sampling procedure used), it is possible that drying the silage samples at 40 °C may have resulted in the loss of some volatile compounds thereby underestimating true DM. However, such losses would have been quite small at this relatively low drying temperature. Finally, effluent was not produced from any of the treatments and consequently did not impact on the findings.

Silage fermentation: Satisfactory fermentation depends on maintaining anaerobic conditions during ensilage and on inhibiting the activity of undesirable anaerobic microorganisms (McDonald *et al.*, 1991). Thus, for bales wrapped in six layers of stretch-film and made from herbage wilted for 72 h, the restricted fermentation (relatively high residual WSC and low fermentation product concentrations) appeared to be dominated by homofermentative lactic acid bacterial activity and evidence for undesirable microbial activity was quite small. Shorter durations of wilting resulted in lower DM concentrations and led to more extensive fermentation that was less dominated by homofermentative lactic acid bacteria and showed more evidence of clostridial activity (i.e., elevated BA and NH_3-N concentrations). These results indicate that the herbage harvested would have been very difficult to preserve had it been ensiled unwilted.

Overall, increasing the density setting of the baler so that mean bale density increased from 371 to 455 kg/m^3 had relatively little effect on the extent or direction of fermentation. This is in accord with the findings of McEniry *et al.* (2007) who showed that the impacts of forage compaction were relatively minor where anaerobic conditions prevail.

Reducing the amount of stretch-film used to wrap baled silage can result in progressively less-anaerobic conditions (Lingvall *et al.*, 1993; Forristal *et al.*, 1999 and 2000). In the present experiment, wrapping bales in four rather than six layers of stretch-film had little impact on fermentation characteristics. In contrast, applying only two layers of stretch-film altered the fermentation resulting in a large elevation in silage pH and NH_3-N values. An explanation for this outcome is that two layers of stretch-film did not create sufficiently anaerobic conditions to allow a satisfactory fermentation to occur thereby allowing for the continued activity of undesirable microorganisms. Other workers have reported that under conditions not unlike those in the present experiment, two layers of stretch-film resulted in a small (Forristal *et al.,* 1999) or no (Forristal *et al*., 2000) disimprovement in fermentation despite an increase in visible surface mould growth. However, the apparent differences between these two sets of studies are likely related to the considerably greater extent of total aerobic damage that occurred in the present experiment when two, four or six layers of stretch-film were used (0.85, 0.05 and 0.01 of surface area, respectively) compared to Forristal *et al*. (1999; 0.21, 0.02 and 0.01 of surface area, respectively) and Forristal *et al*. (2000; 0.20, 0.01, and 0.01 of surface area, respectively).

Silage pH values above 6.0 normally only occur where extensive aerobic deterioration has taken place. In the present experiment silage pH was consistently higher when two rather than four or six layers of stretch-film were used, and this was particularly evident for 24 h wilted low and high density bales, and for the 48 h wilted high density bales. In each of these cases silage pH was at least 6.2, and the associated reductions in lactic acid concentration and increases in ammonia-N concentration relative to the corresponding four and six layers of stretch-film treatments were larger than occurred with 48 h wilted low density bales or with the 72 h wilted low or high density bales.

Nutritive value: During ensilage, ash concentration increased less with W72 herbage (110 to 114 g/kg DM) compared to W24 (100 to 119 g/kg DM) and W48 (103 to 112 g/kg DM) herbages. This likely reflected the lower losses of digestible organic matter during ensilage for the W72 herbage, as a result of its more anaerobic conditions and more restricted fermentation. Similarly, ash concentration increased less when four (104 to 113 g/kg DM) or six (104 to 114 g/kg DM) layers of stretch-film were used compared to two (104 to 128 g/kg DM) layers. This can be explained by the larger loss of digestible organic matter with excessive aerobic microbial activity when only two layers of stretch-film were used. These differences in DM loss during ensilage most likely explain the differences in silage crude protein concentration due to wilting and due to the number of layers of stretch-film used, assuming that the digestible organic matter lost was of low nitrogen content (e.g., WSC and organic acids). However, the NH_3-N values indicate that the quality of the conserved protein deteriorated less with W72 (111 g/kg N) compared to W24 (162 g/kg N) and W48 (150 g /kg N) silages, and for four (125 g/kg N) and six (119 g/kg N) layers compared to two (179 g/kg N) layers of stretch-film.

The numerical decline in *in vitro* DMD during the ensilage of W72 herbage wrapped in six layers of stretch-film was quite modest (726 to 714 g/kg) and this agrees with McDonald and Edwards (1976) who found little change under excellent ensiling conditions. However, where fermentation characteristics disimproved (lower LA/FP and higher NH_3-N concentrations) by wilting herbage for only 24 h or where both fermentation and aerobic deterioration characteristics disimproved by using only two layers of stretch-film, the decline in DMD was much larger. These results agree with Flynn (1981) who found poor preservation to reduce silage DMD (726 to 676 g/kg), and with McEniry *et al.* (2007) who found air ingress to also reduce silage DMD (743 to 703 g/kg).

Conclusion

The two fundamental requirements of all successful silage-making systems are that the herbage is stored under anaerobic conditions throughout ensilage and that the activities of undesirable micro-organisms are restricted or prevented. In farm practice in Ireland, these requirements are facilitated during the production of baled silage by field wilting the herbage prior to baling and by wrapping the bales in polythene stretch-film. The results reported here clearly confirm that bales need to be wrapped in at least four layers of conventional stretch-film – wrapping bales in only two layers of film failed to create the anaerobic conditions required to restrict visible fungal growth on the outer surface of baled silage and to permit a satisfactory fermentation to occur. The extent of the effects of air ingress on the bale surface was greatly diminished when four layers of stretch-film were used, and the further advantages of using six layers of stretch-film were relatively small.

Once sufficient stretch-film was used then the extent of wilting or the density of the bales had relatively little impact on the visible growth of mould. However, more extensive wilting under these relatively anaerobic conditions improved the standard of silage preservation with the evidently difficult-to-preserve herbage used in this experiment.

Acknowledgements

The authors acknowledge the skilled technical input of J. Hamill and J. Marron, silage making by Grange farm staff (especially the input of J. Lynch) and the chemical analyses by Grange Laboratories staff.

References

AOAC (Association of Official Analytical Chemists). 1990. In: “Official Methods of Analysis” (ed. K. Helrick), 15th edition, Virginia, USA, 746 pages.

Flynn, A.V. 1981. Factors affecting the feeding value of silage. In: “Recent Advances in Animal Nutrition” (Ed. W. Haresign), Butterworths, Toronto, Canada, pages 81–89.

Forristal, P.D., O’Kiely, P., Lenehan, J.J. and Mescall, M.P. 1999. The influence of the number of layers of film cover and film colour on silage preservation, gas composition and mould growth on big bale silage. *Proceedings the XIIth International Silage Conference*, *Uppsala, Sweden*, pages 251–252.

Forristal, P.D., O’Kiely, P., Lenehan, J.J. and Mescall, M.P. 2000. The influence of the number of layers of film cover and stretch level on silage preservation, gas composition and mould growth on big bale silage. *Proceedings of the Agricultural Research Forum*, *Tullamore*, *Ireland*, pages 49–50.

Forristal, P.D. and O’Kiely, P. 2005. Update on technologies for producing and feeding silage. Silage production and utilization. *Proceedings of the XIVth International Silage Conference*, *Belfast, Northern Ireland*, pages 83–96.

Greenhill, W.L. 1959. The respiration drift of harvested pasture plants during drying. *Journal of the Science of Food and Agriculture* **10:** 495–501.

Greenhill, W.L. 1964. Plant juices in relation to silage fermentation. III. Effect of water activity of juice. *Journal of the British Grassland Society* **19:** 336–339.

Hancock, D.W. and Collins, M. 2006. Forage preservation method influences alfalfa nutritive value and feeding characteristics. *Crop Science* **46:** 688–694.

Heikkila, T., Jaakkola, S., Saarisalo, A., Suokannas, A. and Helminen, J. 2002. Effects of wilting time, silage additives, and plastic layers on the quality of round bale silage. *Proceedings the XIIIth International Silage Conference*, *Auchincruive, Scotland*, pages 158–159.

Huhnke, R.L., Muck, R.E. and Payton, M.E. 1997. Round bale silage storage losses of ryegrass and legume-grass forages. *Applied Engineering in Agriculture* **13:** 451–457.

Jacobsson, F., Lingvall, P. and Jacobsson, S.O. 2002. The influence of stretch film quality, number of layers and type of baler on bale density, silage preservation, mould growth and nutrient losses on big bale silage. *Proceedings the XIIIth International Silage Conference*, *Auchincruive, Scotland*, pages 164–165.

Lingvall, P. 2002. The bale silage technology. Factors influencing silage fermentation, hygienic quality, storage stability and production costs. *Proceedings the XIIIth International Silage Conference*, *Auchincruive, Scotland*, pages 162–163.

Lingvall, P., Pettersson, C.M. and Wilhelmsson, P. 1993. Influence of oxygen leakage through stretch film on quality of round-bale silage. *Proceedings of the XVII International Grassland Congress, New Zealand*, pages 600–601.

McDonald, P. and Edwards, R.A. 1976. The influence of conservation method on digestion and utilisation of forages by ruminants. *Proceedings of the Nutrition Society* **35:** 201–211.

McDonald, P., Henderson, N. and Heron, S.J.R. 1991. "The Biochemistry of Silage". Chalcombe Publications, Marlow, UK, 340 pages.

McEniry, J., O'Kiely, P.O., Clipson, N.J.W., Forristal, P.D. and Doyle, E.M. 2006. The microbiological and chemical composition of baled and precision-chop silages on a sample of farms in County Meath. *Irish Journal of Agricultural and Food Research* **45:** 73–83.

McEniry, J., O'Kiely, P.O., Clipson, N.J.W., Forristal, P.D. and Doyle, E.M. 2007. The relative impacts of wilting, chopping, compaction and air infiltration on the conservation characteristics of ensiled grass. *Grass and Forage Science* **62:** 470–484.

McEniry, J., O'Kiely, P.O., Clipson, N.J.W., Forristal, P.D. and Doyle, E.M. 2008. The microbial and chemical composition of silage over the course of fermentation in round bales relative to that of silage made from unchopped and precision-chopped herbage in laboratory silos. *Grass and Forage Science* **63:** 407–420.

McNamara, K., O'Kiely, P., Whelan, J., Forristal, P.D. and Lenehan, J.J. 2002. Simulated bird damage to the plastic stretch-film surrounding baled silage and its effects on conservation characteristics. *Irish Journal of Agricultural and Food Research* **41:** 29–41.

McNamara, K., O'Kiely, P., Whelan, J. and Forristal, P.D. 2004. Simulated bird damage to the plastic film surrounding baled silage of differing dry matters. *Grassland Science in Europe* **9:** 990–992.

O'Brien, M., O'Kiely, P., Forristal, P.D. and Fuller, H.T. 2007. Visible fungal growth on baled grass silage during the winter feeding season in Ireland and silage characteristics associated with the occurrence of fungi. *Animal Feed Science and Technology* **139:** 234–256.

O'Brien, M., O'Kiely, P., Forristal, P.D. and Fuller, H.T. 2008. Fungal contamination of big-bale grass silage on Irish farms: predominant mould and yeast species and features of bale and silages. *Grass and Forage Science* **63:** 121–137.

O'Kiely, P., Forristal, P.D., Brady, K., McNamara, K., Lenehan, J.J., Fuller, H. and Whelan, J. 2002. Improved technologies for baled silages. Beef Production Series # 50, 128 pages.

Ranfft, K. 1973. Determination by gas chromatography of short chain fatty acids in ruminal fluids. *Archives Tierernahrung* **23:** 243–352.

SAS. 2000. Version 8.02. SAS Institute Inc., Cary, NC, USA.

Tilley, J.M.A. and Terry, R.A. 1963. A two-stage technique for the *in vitro* digestion of forage crops. *Journal of the British Grassland Society* **18:** 104–111.

Wilson, R.K. 1978. Estimation of water-soluble and individual carbohydrates in grass samples. *Proceedings of Euro Analysis*, *Dublin, Ireland, No. 3*, page 46.

Woolford, M.K. 1975. Microbiological screening of the straight chain fatty acids (C_1-C_{12}) as potential silage additives. *Journal of the Science of Food and Agriculture* **26:** 219–228.

Received 24 April 2009